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Identification of sediment sources in a small rural drainage basin

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Abstract In this study, the fingerprinting method, which uses geochemical variables to distinguish sediment sources and classify suspended sediments through multivariate statistical analysis, was applied to a small rural drainage basin in southern Brazil. The drainage basin represents a typical agricultural ecosystem, in which peasants cultivate tobacco in fragile areas (headwaters), liable to severe erosion. By classifying suspended sediments, it was possible to identify the relative contribution from different sources and thus to suggest actions that would limit soil loss. Results showed that the predominant contribution was from fields and roads, contributing 64% and 36%, respectively, of the sediments sampled in the drainage basin control section, with the relative proportion of contribution from each source varying over time and according to management and soil cover in the fields and maintenance-work performed on the roads.

Key words Brazil; composite fingerprinting technique; sediment sources; small drainage basin monitoring

INTRODUCTION

In southern Brazil, peasants cultivate tobacco (*Nicotiana tabacum*) on steep hillsides with shallow soils. In addition to the poor agricultural potential of the land, typical management practices mean that the soil is intensively worked during the period when rainfall is most erosive. This combination of factors favours soil degradation and elevated sediment yield. To solve these problems and to reduce the associated rural poverty, publicly and internationally-financed conservation programmes are being implemented, with the goal of reducing land degradation by controlling soil erosion. The effects of implanting conservation practices on the natural resource base have been evaluated through rural drainage basin monitoring programmes, studying aspects related to hydrology, water quality and sediment yield.

Since sediments originate from a mixture of different sources (roads, fields, pastures and channel banks), it is useful, as part of the monitoring process, to be able to quantify not only the change over time in sediment yield, but also to identify the sources of the sediment, enabling more conclusive results to be drawn about the effect of conservation practices in reducing sediment yield. With this goal in mind, the fingerprinting technique was evaluated for its potential in identifying the origins of eroded sediments in a rural drainage basin.

BACKGROUND

Suspended sediments originate from different sources, with the relative contribution from each source varying over time and space as a consequence of the different erosion processes

Table 1 Chemical properties of sediment source areas.

Element	Pasture	Fields	Unpaved roads	New fields	Channel bank
Fe-total (%)	6.96	7.57	5.01	5.52	2.27
Fe-dithionite (%)	4.20	3.93	2.94	3.33	nd[1]
Fe-oxalate (%)	0.75	0.50	0.29	0.49	nd[1]
Al-total (%)	4.78	4.57	3.16	3.55	3.61
Al-dithionite (%)	0.40	0.34	0.29	0.23	nd[1]
Al-oxalate (%)	0.19	0.18	0.12	0.13	nd[1]
Mn-total	0.09	0.13	0.06	0.09	0.07
Mn-dithionite (%)	0.05	0.07	0.03	0.05	nd[1]
N-total (%)	0.19	0.17	0.08	0.17	0.11
COT (%)	1.94	1.84	0.67	2.21	1.43
Ca (%)	0.05	0.09	0.18	0.13	0.11
P-total (mg kg^{-1})	551.83	770.83	328.33	541.33	479.00
Na (mg kg^{-1})	67.00	76.00	128.33	52.67	867.32
Co (mg kg^{-1})	17.17	26.00	16.33	22.33	11.67
Cr (mg kg^{-1})	10.22	12.95	9.20	7.65	4.48
Zn (mg kg^{-1})	177.17	222.67	211.67	229.17	48.28

nd[1] not determined.

at work in the drainage basin. Much research currently focuses on developing methods that enable these sediment sources to be identified (Symader & Strunk, 1992; Coleman & Scatena, 1986; Horowitz, 1991; Salomons & Stigliani, 1995; Collins & Walling, 2002). One of the most promising of these methods, notable for its efficiency and ease of use, is the fingerprinting technique (Peart & Walling, 1986; Peters *et al.*, 1993; Peart, 1995; Collins *et al.*, 1997; Walling *et al.*, 1999; Walling & Collins, 2000; Collins & Walling, 2002). This method is based on the principle that sediments in suspension maintain some of the geochemical properties of their source material, and that these properties can thus be used as tracers (Table 1).

METHODS

The study area in southern Brazil (Fig. 1) consists of a small rural drainage basin in the headwaters of the Lajeado Ferreira stream, a tributary of the Guaporé River. The area of the drainage basin is 133 ha; however the sediment source study took place in a sub-basin of 57 ha, designated SB1, as identified in Fig. 1. In the larger drainage basin, topography is predominantly rolling (average gradient 7%) with poorly developed soils (average depth 0.50 m), primarily Inceptisoils and Entisoils. The drainage area of SB1 has an average slope of 8%, with a total concentration time of about 30 min.

The land in SB1 is used for tobacco cultivation (31%), pasture (29%), fallow (37%), unpaved roads and paths (3%). Tobacco is grown under traditional management practices, in which draft animals are used to plough the soil during the months of August and September, which correspond with the periods of highest rainfall erosivity. These conditions, in conjunction with the removal of riparian vegetation, favour the process of soil erosion and sediment yield from the fields. In 2002, approximately 57 t km^{-2} year^{-1} of sediment was produced (Merten & Minella, 2003).

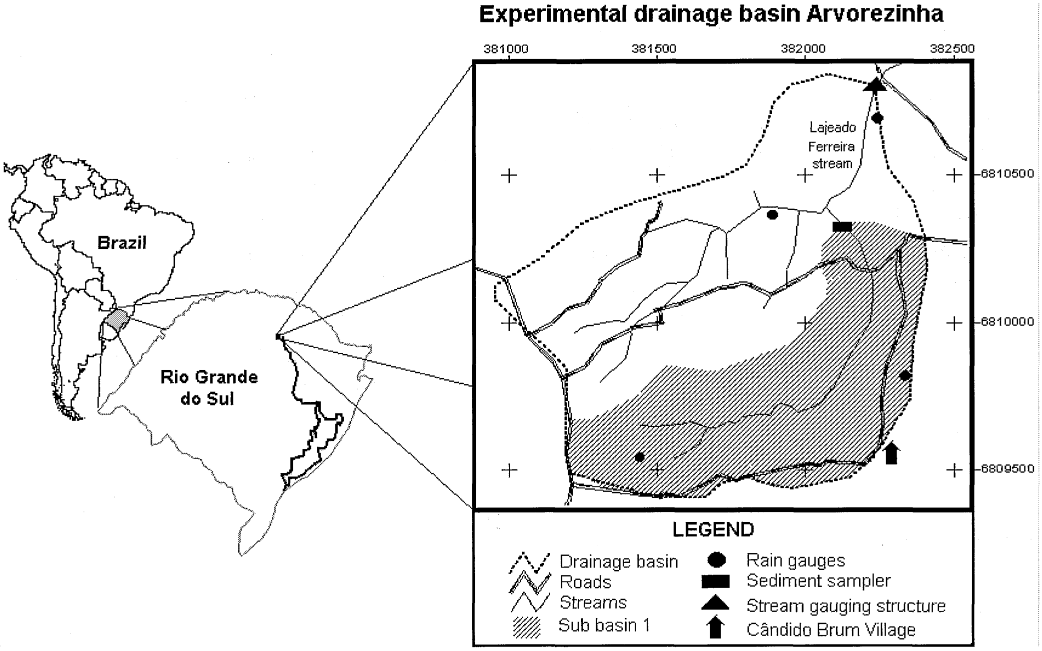

Fig. 1 Location of the study basin on the upper Lajeado Ferreira River.

Flow measurements and suspended sediment and water quality samples have been obtained for a site on the Lajeado Ferreira stream where a Parshall flume has been installed (Fig. 1). Suspended sediment samples were obtained at the location in SB1 shown in Fig. 1 using a sampler similar to the single-stage sampler for suspended sediment (FISP, 1961) in which runoff was stored in a 20-l plastic drum. Modifications made to this equipment enabled sediment samples to be collected during the rising and falling limbs of flood flows (Minella, 2003).

Potential sediment sources were selected after a survey of SB1 to identify the erosion processes operating in the study area. Sources included old and new fields (recently fallow ploughed), pasture, fallow areas, unpaved roads and channel banks. Soil samples from these sources were collected using a trowel, after cutting a small trench in the uppermost layer of the soil (0–0.05 m) which was visibly affected by soil erosion. Six samples were collected to represent each source, with each sample being composed of 10 sub-samples. The amount of material collected for each sample was about 0.5 kg. The samples were dried in the shade and sieved through a 2000 μm sieve before being sent for physical-chemical analysis. Suspended sediment samples were collected between the months of April and October 2002. Ten events were monitored during the course of 1 year. Samples were collected throughout each event (rise, peak and fall). To separate sediment from water, samples were decanted and then dried at 40°C. Samples from ten floods were collected during a period that included road works and changes in soil usage.

Granulometric analysis of the source material and suspended sediment samples was performed using different methods, including laser diffractometry, sieving and pippetting (Minella *et al.*, 2002).

Total levels of N, P, K, Ca, Na, Mg, Cu, Pb, Cr, Co, Zn, Ni, Fe, Mn and Al were measured by extraction after digestion with sulphuric acid (Tedesco, 1995); total organic C was measured by the Walkley-Black method (Tedesco, 1995); Al^{3+} by extraction with KCl (1 M) and titration with NaOH (Tedesco, 1995); Fe and Mn oxides by extraction with dithionite-citrate sodium bicarbonate (Inda Junior, 2002); and Fe oxide by extraction with ammonium acid oxalate (Inda Junior, 2002).

A correction factor $Z_{si} = C_o[100/(100 - F_{ars})]$ was used to correct the concentrations of the chemical elements determined as a function of the granulometric analysis, in which Z_{si} is the corrected concentration of the source (s) and of the chemical element analysed (i); C_o is the average original concentration of the element, and F_{ars} is the percentage of the fraction of the source samples greater than 63 μm (Horowitz, 1991). To assess the potential for discriminating the sources, a number of statistical tests were used, while source ascription for the suspended sediment samples was undertaken using an "optimized sediment mixing model", both of which are described by Walling & Collins (2000).

RESULTS

Assessment of source discrimination potential

The discriminant analysis evaluated five different possible sediment sources: fields (*L*), unpaved roads (*E*), new fields (*LR*), pasture (*P*) and material from the channel banks (*B*). Fallow areas, when analysed by the Kruskall-Wallis test, could not be distinguished from pasture and for this reason were combined with pasture sources. New fields and channel banks did not provide enough data for use in the identification analysis.

For the other sediment sources, the variables that presented discriminatory potential as measured by the Kruskall-Wallis test were: organic carbon (C_{org}), total phosphorus (P), total nitrogen (N), total manganese (Mn_{tot}), total iron (Fe_{tot}), iron dithionite (Fe_{dit}), iron oxalate (Fe_{oxa}), manganese dithionite (Mn_{dit}), total (Al_{tot}), aluminium dithionite (Al_{dit}), aluminium oxalate (Al_{oxa}), total sodium (Na) and total cobalt (Co).

The results of a multivariable analysis of variance, determined using Wilks' lambda (Λ^*), which can be tested using Snedecor's F and the χ^2 distribution as approximations, determined the group of variables that optimized source discrimination and reduced dimensionality. All the possible variables were tested in the variance analysis and those that presented the lowest Λ^* value and significance for the F and χ^2 tests were chosen for use in the classification model. Considering three sediment sources (field, unpaved road and pasture) the best composition was Fe_{tot}, Fe_{oxal}, Al_{oxal}, Mn_{tot}, Ca and P. Considering only two sediment sources, field and unpaved road, there were two optimal compositions: (a) Fe_{tot}, Fe_{oxal}, Fe_{dit}, Al_{oxal}, P and Co; and (b) Fe_{tot}, Fe_{oxal}, Al_{oxal}, Mn_{dit}, P and Co (Table 2).

Besides finding the set that minimized the Λ^* value, another objective of this evaluation is to use the set to explore the different processes associated with soil erosion and sediment transport. The variables should reproduce different mechanisms that occur in their respective sources, such as weathering, redox conditions and soil management. This goal was achieved, as the proposed set presents variables associated with soil management (P and Ca), weathering processes and redox conditions (iron, manganese and aluminium oxides) and the presence of trace metals (Fe_{tot}, Mn_{tot} and Co).

The variables total organic carbon (COT) and total nitrogen (N) were not used as trace variables, despite being selected by the discriminant analysis. The concentrations of these

Table 2 Best sets of tracer variables determined by MANOVA.

	Sources (g = 3): *L, P, E*	sources (g = 2): *L, E*	
	Variables (p = 6): Fe_{tot}, Fe_{oxal}, Al_{oxal}, Mn_{tot}, Ca, P	Variables (p = 6): Fe_{tot}, Fe_{oxal}, Al_{oxal}, Fe_{dit}, P, Co	Variables (p = 6) Fe_{tot}, Fe_{oxal}, Al_{oxal}, Mn_{dit}, P, Co
$\Lambda^* = \lvert W \rvert / \lvert B+W \rvert$	0.0057	0.0563	0.0428
test F			
Λ^* distribution	$[(\sum n - p - 2)/p][(1 - \sqrt{\Lambda^*})/\sqrt{\Lambda^*}] \sim F_{2p,\, 2(\sum n - p - 2)}$	$[(\sum n - p - 1)/p][(1 - \Lambda^*)/\Lambda^*] \sim F_{p,\, (\sum n - p - 1)}$	
Statistical test	20.34	13.97	18.63
$F_{v1,v2}$ (α)	$F_{12,\,20}(0.05) = 2.54$	$F_{6,\,5}(0.05) = 4.95$	
H_o	rejected	rejected	rejected
Chi-square χ^2			
Chi-square distribution	$-[n - 1 - (p + g)/2]\ln(\Lambda^*) > \chi^2_{p(g-1)}(\alpha)$	$-[n - 1 - (p + g)/2]\ln(\Lambda^*) > \chi^2_{p(g-1)}(\alpha)$	
Statistical test	64.51	20.14	22.06
$\chi^2_{p\,(g-1)}$ (α)	χ^2_{12} (0.05) = 19.7	χ^2_6 (0.05) = 12.6	
H_0	rejected	rejected	rejected

H_0, no-treatment effects;
B, treatment sum of squares and cross-products;
W, residual sum of squares and cross-products;
n, sample size.

elements in suspended sediment exceeded the capacity of the correction factors. The most probable hypothesis is that, along with the variability of biomass production over time, the load of soluble fertilizers and animal waste released into the drainage system increased the adsorption of N and COT by the sediment. Animal waste (from confined pork production) is released directly into the streams. Thus, N and COT are much higher in the sediment samples than in the soil (Merten & Minella, 2003).

Discriminant analysis determined the existence of variable sets capable of discriminating sediment sources. Classification analysis, performed with an optimization algorithm, was applied to these options, testing the hypothesis that there are a maximum number of possible sources that can be identified by the model, and the influence of the different variables on the model results is evaluated. The efficiency of the model and the applicability of the results were evaluated by relative average error and by comparing results with field observations.

Source ascription for suspended sediment samples

The results of classifying suspended sediment samples in terms of three possible sources (field, unpaved road and pasture) were inadequate. Relative average errors were greater than 54% for all events. The estimated proportions (regression coefficients) were: fields (0.8%), roads (21.3%) and pasture (77.9%). The use of three adjustable regression coefficients significantly increased the margin of error. According to Walling & Collins (2000), estimates with errors greater than 15% should not be used. Field observations confirmed the inconsistency of the results, as it was quite clear that the contribution from fields and unpaved roads was greater than estimated, and that the contribution from pastures was less. However, the model did not present a viable solution within the limits imposed by the errors and with results that conformed to field observations.

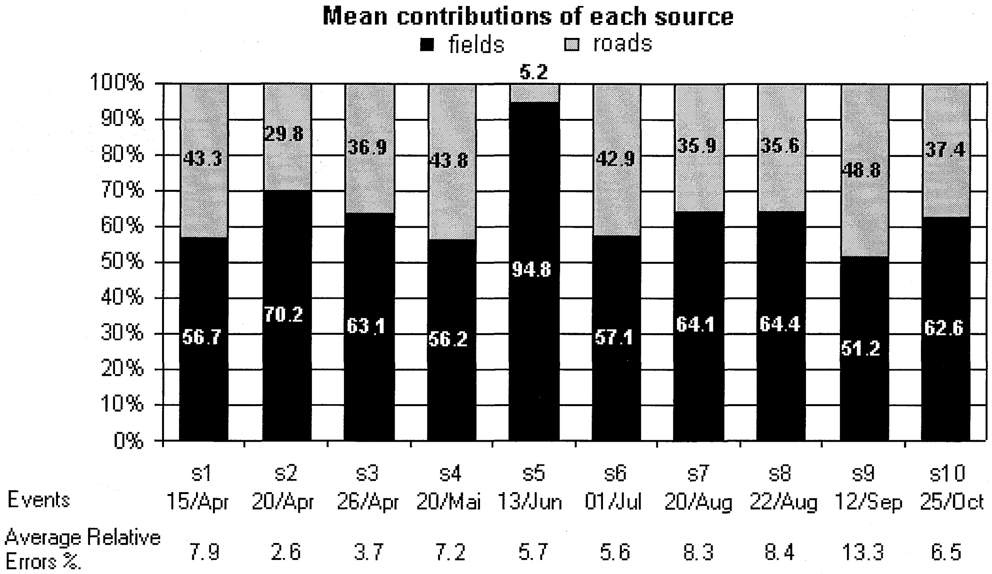

Fig. 2 The relative contributions per event from field and unpaved road sources, showing average relative errors per event.

Based on field evidence and observations of erosion and deposition processes, the hypothesis that unpaved roads and fields are the preponderant sources of sediment was tested. The optimization model found a solution within an acceptable margin of error, 6.92% on average. The relative contributions from each source are presented in Fig. 2. The average contributions were 64% and 36% from fields and from unpaved roads, respectively.

The average relative error is the mean of the sum of the square of the residuals of each variable. This measure is important as it enables one to evaluate individually the behaviour of each of the variables within the linear optimization model.

A wide variation in the relative contribution from each source was observed over time. The average and the coefficient of variation (CV) for the field source were 64% and 19%, respectively. For the unpaved roads, the average was 36% and the CV was 33%. This variability confirms the hypothesis that sediment yield fluctuates depending on factors controlling sediment production and transfer throughout the year.

Considering Fig. 2 and excluding event s5 from the analysis, we see a clear fluctuation in the relative contribution of sediment from the two sources. After April, the soil cover increased, gradually, reducing the contribution from the field source during events s2, s3 and s4. Event s1 also followed this tendency, but there was road-straightening work in early April which increased the contribution from the unpaved roads and, as a result, decreased the relative contribution from the fields.

Between the months of August and September, the fields were ploughed and the results showed a gradual increase in the relative contribution from the fields (s6, s7, s8). Nonetheless, with road-straightening in early September, there was once again an increase in the relative contribution from the unpaved roads.

The results show that the application of the fingerprinting technique for identification of sediment sources was reasonably sensitive to the factors that influenced the proportions of sediment contributed in the drainage basin studied. Future studies using this technique will emphasize the identification of conservative geochemical properties sensitive to changes in soil management, especially by different soil tillage systems. For the purpose of this study, however, the identification of sediment sources showed that conservation practices, as part of the natural resources management programme, should also include strategies to reduce sediment mobilization from unpaved roads.

CONCLUSIONS

The use of the fingerprinting method for identifying sediment sources proved adequate and practical for the purpose proposed in this study, in which fields and unpaved roads were shown to be the most significant sources of sediment. It was also shown that the relative contribution from each source varied over time, depending on plant cover in the drainage basin and unpaved road maintenance work performed during the study period.

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